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Double beta decay: experimental review

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Abstract

The search of the double beta decay without neutrino emission is currently the only way to test the nature, Dirac or Majorana, of the neutrino. Two different experimental approaches exist: one, where source and detector coincide, is pure calorimetric (Germanium detectors like GERDA, MAJORANA, bolometer CUORICINO/CUORE, CdZnTe semi-conductors COBRA). In the other technique, before the measurements of their energies, the two electrons are tracked (tracking chamber and plastic scintillators for NEMO3/SuperNEMO and Xenon TPC for EXO). The results of the currently data-taking experiments (CUORICINO and NEMO3) are presented. The expected sensitivities for future experiments are discussed.

1 The double beta decay process $\beta\beta0\nu$

1.1 The $\beta\beta0\nu$ process as a way to test physics beyond the standard model

The double decay process $\beta\beta0\nu$, in which 2 neutons simultaneously desintegrate into two protons and two electrons, violates the global lepton number conservation by $\Delta L = 2$. This process can be explained by the exchange of a massive Majorana neutrino, with an effective neutrino mass $< m_\nu >$. The rate R of the process is given by:

$$R = < m_\nu >^2 \times PS \times |M_{nucl}|^2 \qquad (1)$$

where PS is the phase space factor and M_{nucl} the nuclear matrix element.

The double-beta $\beta\beta0\nu$ process can also explained by the existence of right-handed current in weak interactions, or by the exchange of a SUSY particle. In the process with Majoron emission, part of the energy delivered by the desintegration is taken away by the Majoron particle, so that the 2-electron energy has in that case a continuous spectrum, and not a peak in energy (see figure 1).

1.2 The experimental approaches to detect the $\beta\beta0\nu$

The first approach is purely calorimetric: source and detector coincide. This technique is used by Ge semi-conductor detectors for GERDA and MAJORANA experiments, by CdZnTe semi-conductor detectors for CANDLE experiment, by Te bolometers for CUORICINO/CUORE experiments. With this technique, a very high energy resolution and a good efficiency can be obtained. The detectors can be made compact and the crystals can be made very pure; however they still can have some surface contamination in isotopes which produce a background for the $\beta\beta0\nu$ decay. These detectors don't give a signature of the 2 electrons, and have only one observable, which is the total deposited energy.

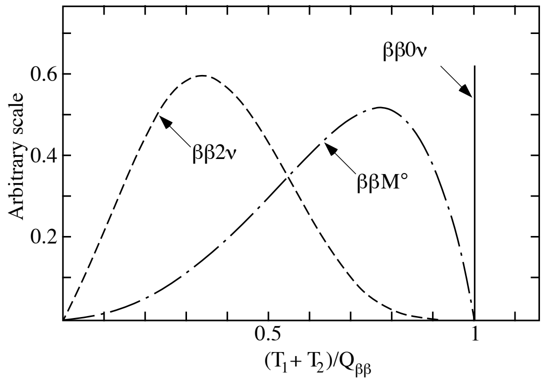

Figure 1: Theoretical 2 electron-energies spectrum, normalised to the Q-betabeta value, for the $\beta\beta0\nu$ process (solid line), for the $\beta\beta2\nu$ process (dashed line) and for the Majoron emission (dotted line).

In the second technique, firstly the electrons emerging from the betabeta source are detected in a tracking detector, then their energies are measured in a calorimeter. This technique is used by the NEMO and EXO experiments. The technique allows to measure the total deposited energy, the individual energy and the angular correlation. Several isotopes can be measured with this approach. The energy resolution and efficiency are limited, and the size of the detector has to be quite large.

Both techniques are complementary and at least 2 or 3 experiments are needed to really prove the $\beta\beta0\nu$ decay at a level of 5 sigma.

2 The pure calorimetric experiments

2.1 The Germanium experiments GERDA and MAJORANA

Two projects use Germanium diodes: GERDA and MAJORANA. The main difference between these experiments is that GERDA will use a cryogenic liquid shield, made of liquid nitrogen or of liquid argon whereas MAJORANA plans to use an electroformed copper shield. So GERDA can use the detection of scintillation light in liquid argon to reject events produced by the interaction of an external gamma.

The background reduction techniques are similar:

- muon veto, to reject cosmogenic events produced by muons
- anti-coincidence between detectors, to reject background produced by multi-Compton events
- segmentation of readout electrodes, also to reject multi-site background events
- pulse shape analysis, also to reject multi-site background events
- coincidence in decay chain, to reject background coming from ^{68}Ge

The GERDA experiment will be installed in the LNGS underground laboratory. In the first phase, using the crystals from the Heidelberg-Moscow and IGEX experiments (15 kg of ^{76}Ge), after one year of data-taking, the experiment could confirm or reject the signal that a part of the Heidelberg-Moscow collaboration claim they observed. In the second phase, the experiment will use 35 kg of segmented crystals of ^{76}Ge and with a background level of 10^{-3} count/(keV.kg.y), they could exclude at 90% CL a half-time decay of 2 10^{26} y at 90 % CL for the $\beta\beta0\nu$ process after 3 years of data taking. In the third phase, with a mass of 100 kg of segmented crystals of ^{76}Ge, a background level of 10^{-3} count/(keV.kg.y) and 10 years of data taking, the experiment could exclude a half-time decay of 2 10^{27} y. In September 05, the experiment has enriched 37.5 kg of ^{76}Ge at the level of 88%. In April 06, the enriched material has been transported to Germany in a special steel container, which reduces the activation by the cosmic rays by a factor 20. Now the enriched material is stored underground in HADES in Germany.

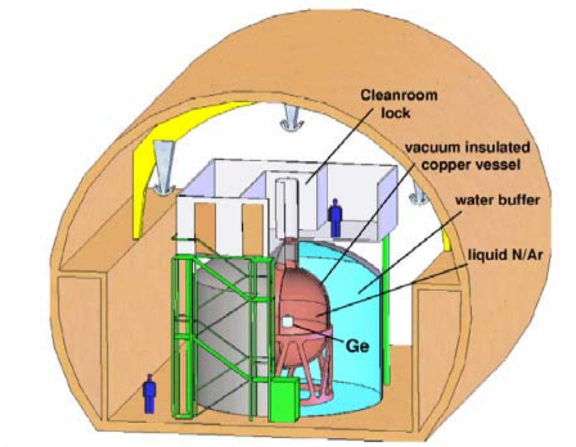

Figure 2: Schematic view of the GERDA experiment. The ^{76}Ge crystals are surrounded by a liquid nitrogen or liquid argon shielding.

The MAJORANA project in the US planes to use in last phase 210 high-purity segmented diodes of 500 kg of enriched Germanium. In the first phase the experiment will use 60 kg of enriched Germanium, then 120 kg. Probably the two projects will merge in the last phase.

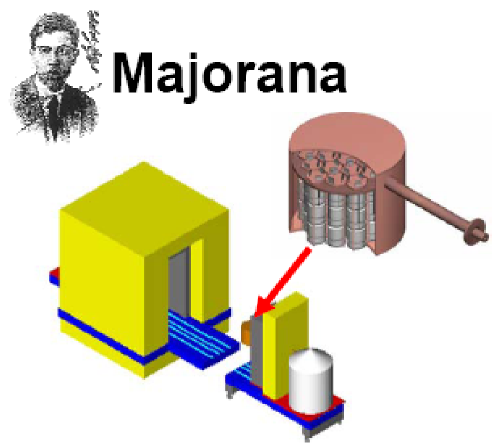

Figure 3: Schematic view of the MAJORANA experiment. The ^{76}Ge crystals are surrounded by an electroformed copper shielding.

2.2 The bolometric experiments CUORICINO/CUORE

The CUORICINO experiment is currently taking data in the LNGS laboratory (Gran Sasso). It consists in a bolometer made of 44 crystals of 790 g and of 18 crystals of 330 g of Tellurium, which represents a total mass of 11.64 kg of ^{130}Te. The crystals are placed in a shielding made of a copper box and Roman lead inside the cryostat, and of 20 cm of lead and 10 cm of borated polyethylene outside.

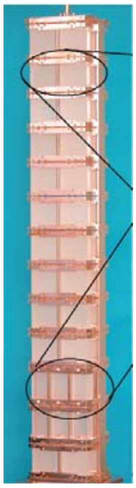

Figure 4: The CUORICINO experiment, which is a tower made of crystals of natural Tellurium.

With an exposure of 8.38 kg of ^{130}Te. year, a background level of 0.18$\pm$ 0.01 count/(keV.kg.y) and a FWHM at 2615 keV of 8 keV, the CUORICINO collaboration excludes at 90% CL a half-time of 2.410^{24}y for the $\beta\beta0\nu$ process. The expected sensitivity after 5 years of data taking is around 810^{24}y.

The CUORE project is an extrapolation of the CUORICINO detector. It will consist in an array of 988 crystals of TeO_2, which represent a TeO_2 mass of 741 kg, so a mass of ^{130}Te of 200 kg. The goal is to obtain a background level less than 10^{-2} count/(keV.kg.y) and a FWHM at 2615 keV of 5 keV, which induces a sensitivity of 2.1 10^{26} y for the half-time excluded at 90% CL for the $\beta\beta0\nu$ process. It corresponds to an upper limit on the effective Majorana neutrino mass less than 19-100 meV, the range being due to uncertainties in nuclear matrix elements calculations.

The CUORE collaboration is currently involved in an R&D effort to reduce their background. A significative contribution to the background is produced by surface contamination of the copper frames or of the crystal surface. Surface sensitive bolometers have been developped: the idea is that by measuring both the amplitudes and the rise times of the signals in the bolometer and in the surface bolometer it is possible to discriminate between a radioactive desintegration produced inside the bolometer and a desintegration produced on the surface of the bolometer. Scintillating bolometers are also under study. At the same time, the collaboration is also investigating which surface cleaning procedure could be more efficient for the copper frames; compare to the CUORE procedure, the removal of hundred of microns by electropolishing and of few microns by magnetron sputtering in ultra-high vacuum could be promising.

2.3 The Cadmium/Zinc/Tellurium experiment COBRA

The COBRA project consist in a large array of CdZnTe semiconductor detectors. The detectors contain 9 betabeta-isotopes: ^{116}Cd, ^{130}Cd, ^{114}Cd, ^{70}Zn, ^{128}Te ($\beta^-\beta^-$), ^{64}Zn, ^{106}Cd, ^{108}Cd, ^{120}Te ($\beta^+\beta^+$, β^+EC, EC/EC). The main $\beta\beta0\nu$ candidate, the ^{116}Cd, is enriched at 90%. An other isotope, ^{106}Cd gives an enhanced sensitivity to the right-handed weak currents. Currently the COBRA collaboration is testing individual crystals in surface labs and a 4x4x4 array has been installed in the LNGS laboratory.

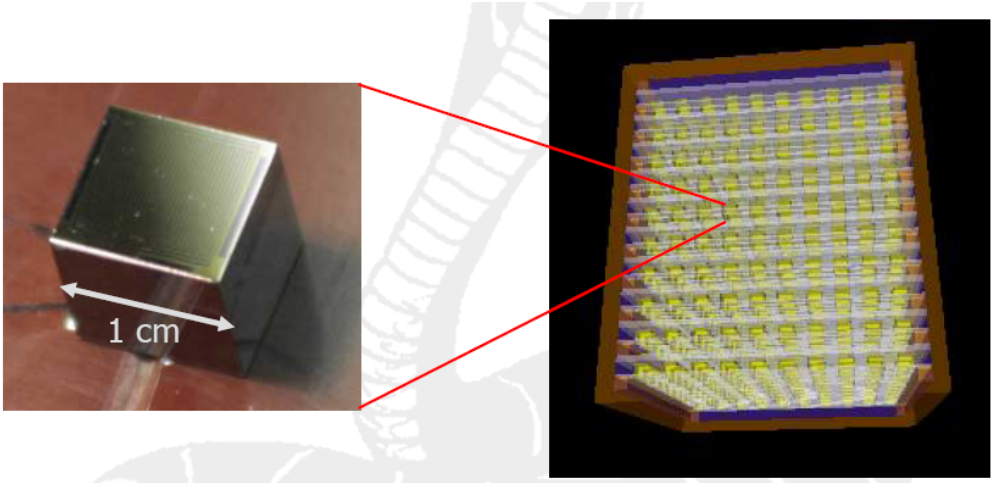

Figure 5: The COBRA project, which consist in a large array of CdZnTe semiconductor detectors.

2.4 The CANDLE project with CaF_2 scintillating crystals

The CANDLE project consists in pure CaF_2 scintillating crystals placed in a liquid scintillator and surrounded by $13''$ and $15''$ PMTs. The prototype CANDLE III is in operation since a few months in Osaka in Japan with 10^3 cm^3 crystals. The energy resolution at 4.2 MeV is around 5% at 4.2 MeV. The total mass is 191 kg of CaF_2, which corresponds to 300 g of ^{48}Ca. The technique could be very promising with enriched ^{48}Ca crystals; however with the current techniques it is very difficult to enrich 100 or 200 kg of ^{48}Ca.

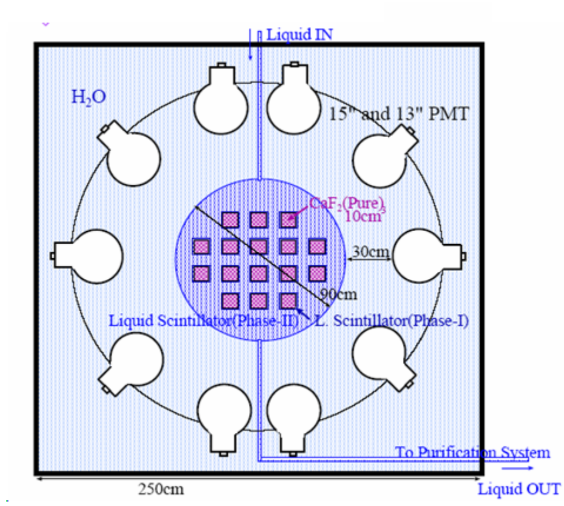

Figure 6: The CANDLE project, which consist in CaF_2 scintillating crystals placed in a liquid scintillator and surrounded by $13''$ and $15''$ PMTs.

3 The tracking and calorimetric experiments

3.1 The TPC with enriched ^{136}Xe: the EXO project

The EXO project consists in a large TPC with enriched ^{136}Xe. The principle of the detector will be to measure the ionisation and the scintillation produced by a $\beta\beta0\nu$ desintegration, and also to tag the Ba^{+} ion produced after a $\beta\beta0\nu$ desintegration of the ^{136}Xe, and so to have a zero-background experiment: if the ion is collected and exposed to a laser beam with an appropriate wavelength, it can reemit a photon with a different wavelength.

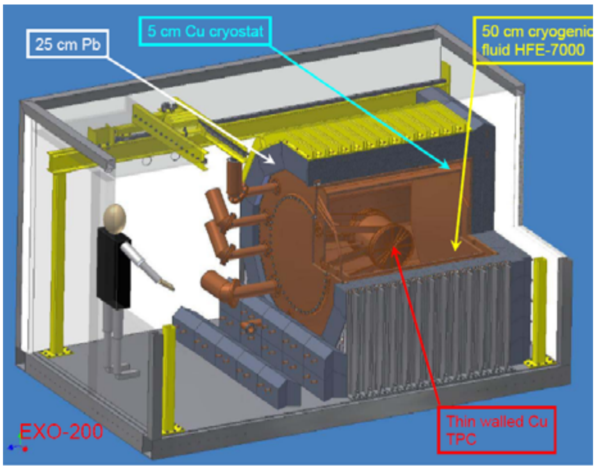

Figure 7: The EXO-200 prototype, which consist in a TPC which 200 kg of enriched ^{136}Xe.

Xenon is a noble gas, so easy to enrich and the EXO collaboration has already obtained 200 kg of enriched ^{136}Xe. The collaboration has already started R&D with a liquid-Xenon prototype, called EXO-200, without identification of the Ba^{+} ion produced. With an energy resolution of 1.6% for the FWHM at 2.5 MeV and a background level of 1.5 10^{-3} count/(keV.kg.y), the expected half-time which can be excluded at 90% CL for the $\beta\beta0\nu$ process is 6.4 10^{25} y after 2 years of data taking.

With 1 ton of ^{136}Xe and the identification of the Ba^{+} ion, a background level of less than 510^{-4} count/(keV.kg.y) could be obtained and a sensitivity greater than 10^{27} years could be reached for the excluded half-time decay at 90% CL of the $\beta\beta0\nu$ process.

3.2 The tracking-calorimeter NEMO experiment

The NEMO-3 detector is currently taking data in the Frejus Underground Laboratory(LSM). It consists in thin foils of betabeta isotopes (^{100}Mo, ^{82}Se, ^{116}Cd, ^{116}Cd, ^{96}Zr, ^{150}Nd, ^{48}Ca) surrounded by a drift-chamber of Helium with 4% of ethylic alcohol, 1% of argon and 0.1% of water. The energies of the electrons are measured by plastic scintillators coupled to low-radioactivities PMTs. The detector is placed in a magnetic field of 25 Gauss and in a gamma shielding of iron and a neutron shielding of borated water and wood. As a too high radon level in the detector has been measured, an anti-radon tent has been installed in 2004 around the detector, in which air is flushed through 1 ton of charcoal at -50^{0}C to trap radon. The NEMO-3 detector has already measured the half-time values of the allowed $\beta\beta2\nu$ process for several isotopes:

$$T_{1/2} = \ 7.11 \pm 0.22(\text{stat}) \pm 0.54(\text{syst})10^{18}\text{y for } ^{100}\text{Mo}$$

$$T_{1/2} = \ 9.6 \pm 0.3(\text{stat}) \pm 1.0(\text{syst})10^{19}\text{y for } ^{82}\text{Se}$$

Preliminary values of these half-time decay have also been obtained for ^{116}Cd, ^{150}Nd, ^{96}Zr and ^{48}Ca.

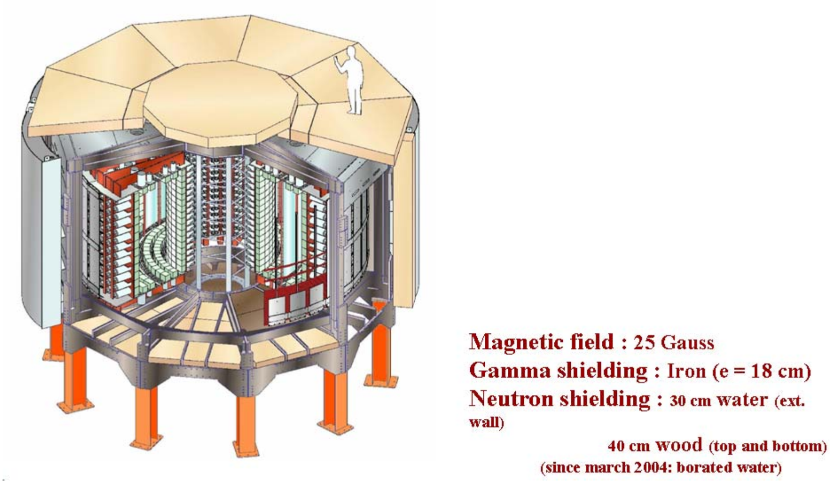

Figure 8: The NEMO-3 detector, where the betabeta isotopes are surrounded by a tracking chamber and plastic scintillators coupled to low-radioactivity PMTs.

Preliminary results have also been obtained for the $\beta\beta0\nu$ process. While combining the data taking in Phase I (298 days, before the installation of the anti-radon tent) and in Phase II (290 days, after the installation of the anti-radon tent) the limits for the half-time excluded at 90% CL for the 7 kg of ^{100}Mo and for the 1 kg of ^{82}Se are respectively 5.8 10^{23}y and 2.1 10^{23}y. After 5 years of data taking, the expected limits are 2 10^{24}y and 8 10^{23}y.

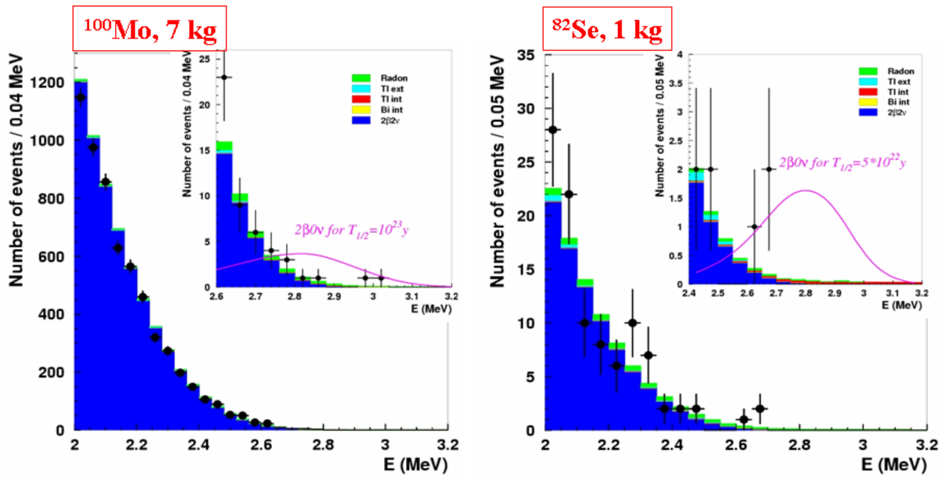

Figure 9: Energy sum distribution above 2 MeV, for two-electrons emitted from the sources of ^{100}Mo and of ^{82}Se, for a data taking time of 588 days (combining Phase I (high radon) and Phase II (low radon) periods).

At the same time, the collaboration has started an 3 years R&D effort in order to build a SuperNEMO detector. The idea is have a large mass, on the order of a few hundred of kilograms of betabeta isotops. Compare to NEMO-3, the goal would be to have a twice better energy resolution (8% instead of 4% for the FWHM at 3 MeV), to win a factor 3 in the $\beta\beta0\nu$ efficiency (25% instead of 8%), to win at least one order of magnitude on the source contaminations (10 μBq/kg of ^{214}Bi instead of 300μBq/kg, 2 μBq/kg of ^{214}Bi instead of 20μBq/kg).

This detector, composed of few tens of planar modules, will need a new cavity, around 70 meter long, either in Frejus Underground Laboratory, or in Canfranc laboratory or in another underground laboratory. The shielding against gammas and neutrons could be made between consecutive modules by a 1.5 meter thick wall of water.

The choice of the best isotopes is not obvious, because of the large uncertainties on nuclear matrix elements. The other criteria for the choice are a favorable phase space factor, a large $Q_{\beta\beta}$ to have a reduced level of background induced by natural radioactivity and the possibility to enrich a significative mass of isotope. The Neodynium 150 has a large space factor, and all nuclear matrix elements are supposed to have the same value, 100 kg of ^{400}Nd gives the same sensitivity for the effective neutrino Majorana mass as 410 kg of ^{82}Se, as 410 kg of ^{130}Te, as 1700 kg of ^{76}Ge and as 400 kg of ^{136}Xe.

An infrastructure called SILVA has been used in the past by the CEA in France to enrich 200 kg of ^{235}U in 2 weeks. With this technique, it is possible to enrich 200 kg of ^{150}Nd in few weeks. Enrichment of ^{96}Zr could be considered. To maintain this installation, a statement has been written by the SuperNEMO collaboration. At the same time, 1.5 kg of ^{82}Se has been enriched with ILIAS funding. The purification techniques of Neodynium and of Selenium are under study.

After 5 years of data taking, the limit obtained at 90% CL on the half-time decay of the $\beta\beta 0\nu$ process could on the order of 10^{26} year for ^{82}Se and of $6 10^{25}$ year for ^{150}Nd (but $6 10^{25}$ year for ^{150}Nd is equivalent to $5 10^{26}$ year for ^{82}Se due to the large space factor).

Due to the high $Q_{\beta\beta}$ value for ^{150}Nd, the contribution of radon and of ^{214}Bi to the background is negligible. Due to the coulombian factor because of the high Z of Neodynium, whereas the half-time decay of the $\beta\beta 2\nu$ process is one order of magnitude less than the one for Selenium, the contribution of $\beta\beta 2\nu$ is one the same order for ^{150}Nd as for ^{82}Se.

4 Conclusion

Two experiments, CUORICINO and NEMO-3, are currently running; they aim to test effective neutrino Majorana masses on the order of a few hundreds of meV.

An R&D effort has started for new experiment with a mass of a few hundreds of kilograms of betabeta isotopes. The goal is to reach a sensitivity of a few tens of meV in effective neutrino Majorana masses.

Neutrinoless double beta decay is a long way but it may be promising.

Table 1: Comparison of sensitivity of currently double-beta running NEMO-3 and CUORICINO experiments and of future projects. The nuclear matrix elements are calculated according to Shell Model Caurier(2004) private comm., Stoica et al.(2001), Suhonen et al.(1998 and 2003), QRPA Rodin, Simkovic, Faessler(2005).

Experiment	Nucleus	Mass (kg)	FWHM at $Q_{\beta\beta}$(keV)	Background Counts/ FWHM.kg.y	$T_{1/2}(0\nu)$ limit (years)	$< m_{\beta\beta}$ limit (meV)	Starting taking data
NEMO-3	^{100}Mo	7	350	~0.5	$2\ 10^{24}$	300-1300	
	^{82}Se	1	350	~0.1	$8\ 10^{23}$	600-1700	
CUORICINO	^{130}Te	10	7	~0.2	$4\ 10^{24}$	250-850	
GERDA Phase 1	^{76}Ge	15	4	0.04	$3\ 10^{25}$	250-780	2008
Phase 2		35	4	0.004	$2\ 10^{26}$	100-290	?
Phase 3		300	4	0.004	$6\ 10^{27}$	20-55	?
SuperNEMO	^{82}Se	100	210	0.01	10^{26}	45-130	2012
	^{150}Nd				$6\ 10^{25}$	70	2012
CUORE	^{nat}Te	200	5	0.05	$2\ 10^{26}$	35-120	2012
	^{nat}Te	200	5	0.005	$6.6\ 10^{26}$	20-65	?
if enriched ^{130}Te	^{130}Te	700	5	0.005	$2\ 10^{27}$	10-40	?
CANDLES III	^{nat}Ca	0.2	200				
if enriched ^{48}Ca	^{48}Ca	200	200	0.1	$4\ 10^{26}$	30-100	?
EXO-200	^{136}Xe	160	50	0.95	$3\ 10^{25}$	90-550	2007
EXO Ba^{+} tag		1000	50	0.025	10^{27}	15-95	?